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**Rozman et al.**

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(54) **INPUT EMI FILTER FOR MOTOR DRIVE INCLUDING AN ACTIVE RECTIFIER**

19/2509 (2013.01); G01R 19/2513 (2013.01);  
G01R 31/007 (2013.01); H02M 2001/123  
(2013.01); H04B 2203/5475 (2013.01)

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CPC ..... G01R 19/2509; G01R 19/2513; G01R  
31/007; H02J 1/10; H02J 1/14  
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**H02P 27/00** (2006.01)  
**H02P 29/00** (2016.01)

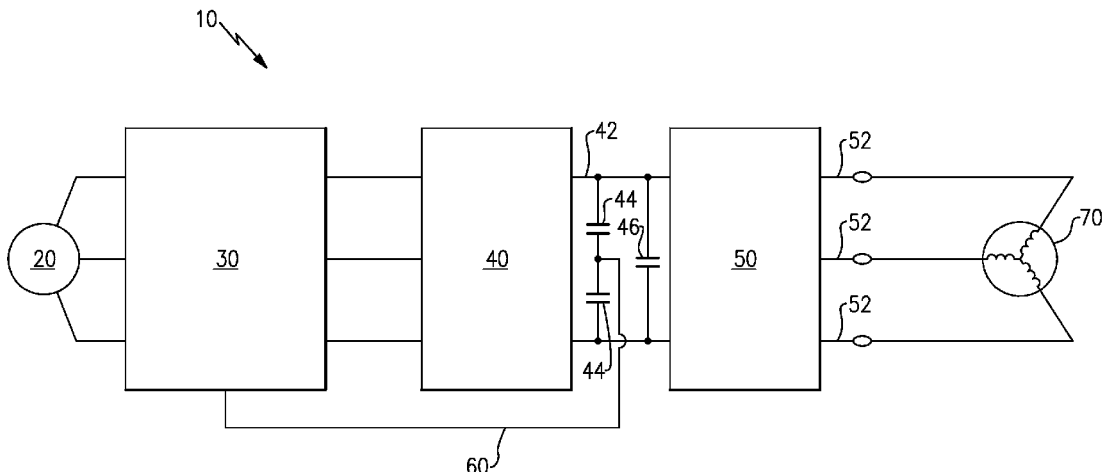
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(57) **ABSTRACT**

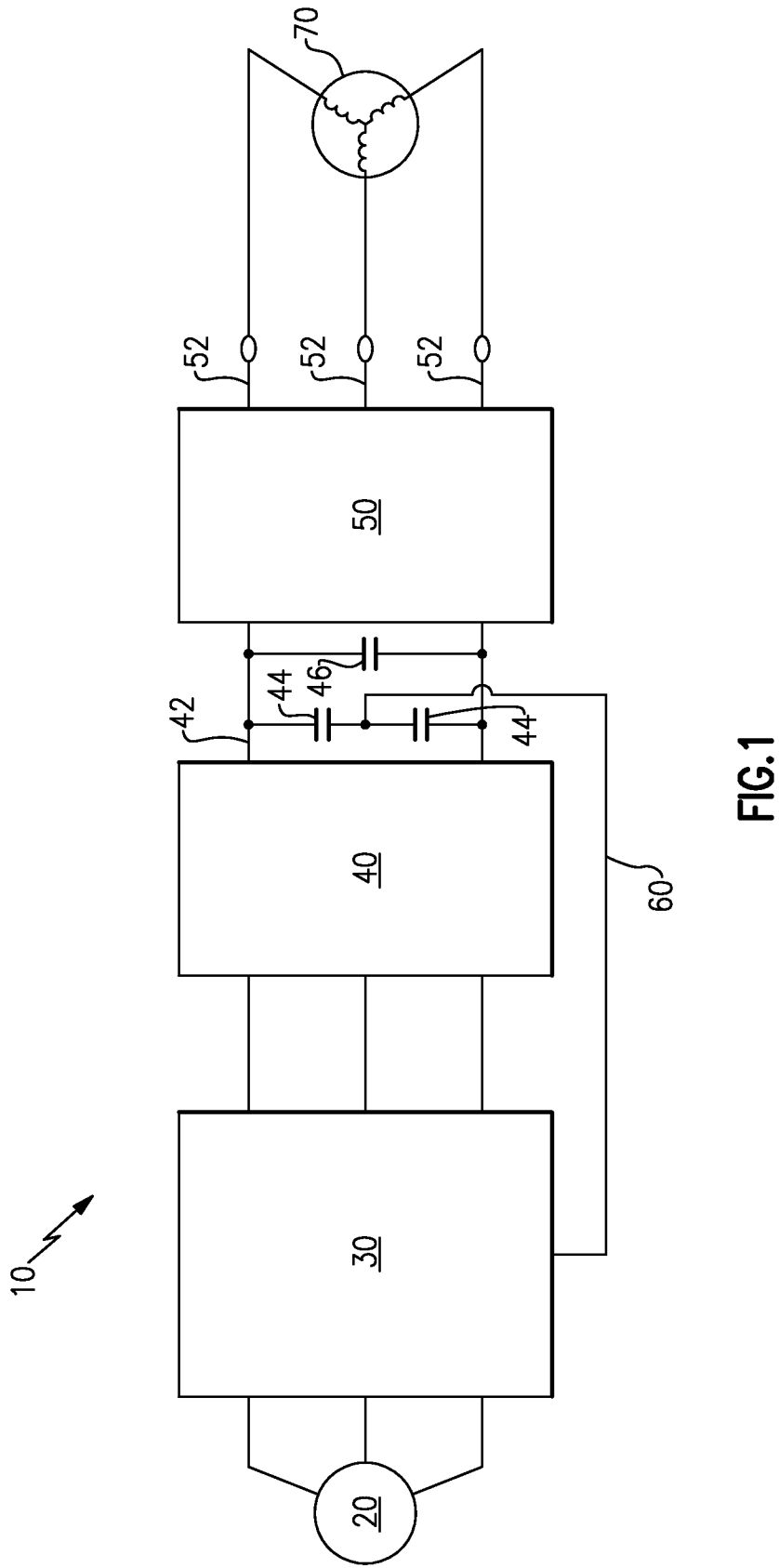
A poly-phase motor drive includes an input EMI filter  
having a poly-phase filter input and a poly-phase filter  
output and an active rectifier connected to the filter output.  
The input EMI filter includes notch filters tuned at active  
rectifier and motor drive inverter switching frequencies and  
diverts common-mode current into DC bus. The active  
rectifier has a DC output. A motor drive inverter is connected  
to the DC output. The motor drive inverter has a poly-phase  
motor control output.

(52) **U.S. Cl.**  
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(2013.01); **H04B 3/30** (2013.01); **G01R**

**11 Claims, 3 Drawing Sheets**



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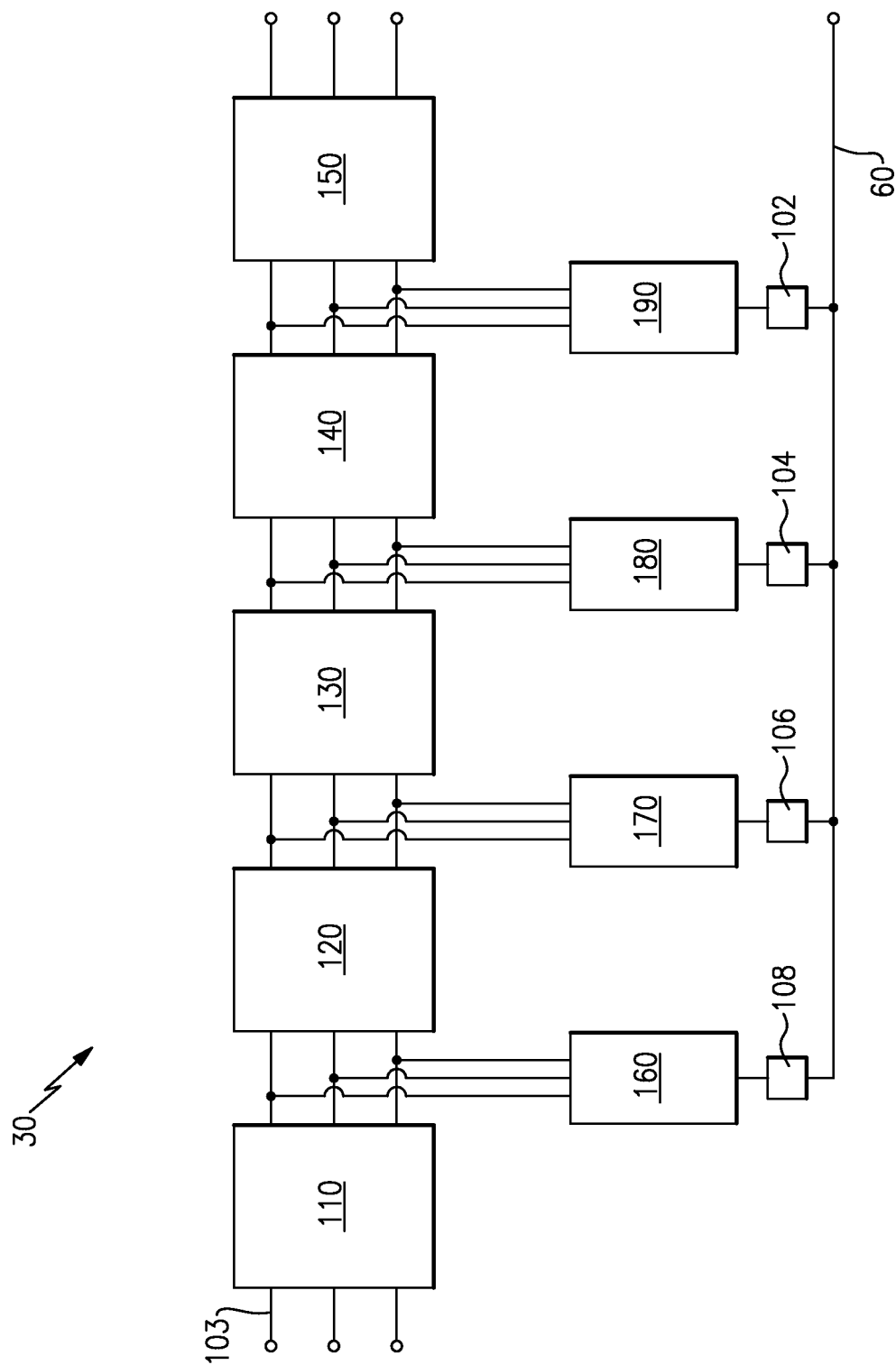


FIG.2

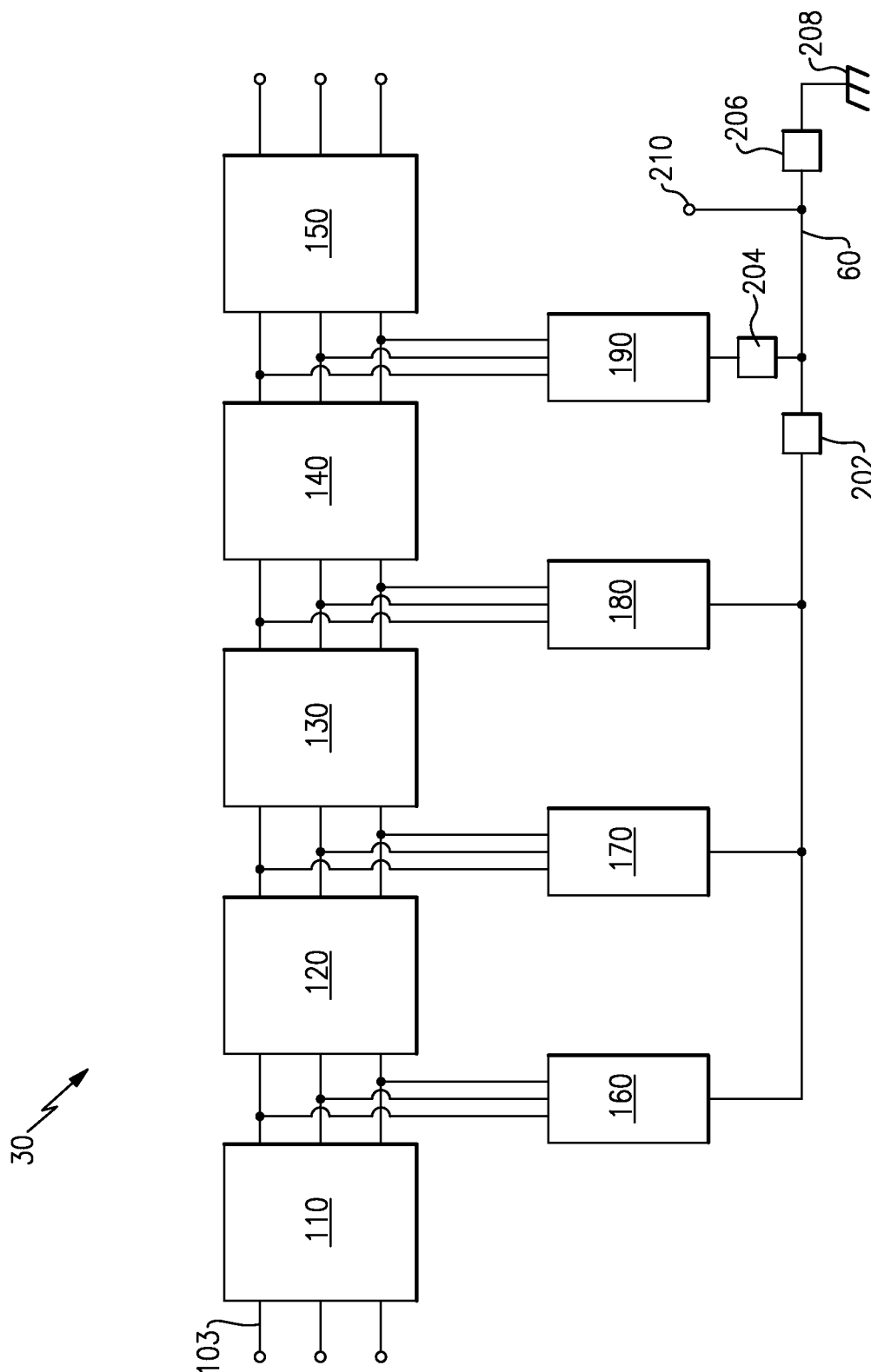


FIG.3

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# INPUT EMI FILTER FOR MOTOR DRIVE INCLUDING AN ACTIVE RECTIFIER

## CROSS REFERENCE TO RELATED APPLICATION

This application claims priority to U.S. Provisional Application No. 61/907,426 which was filed on Nov. 22, 2013.

## STATEMENT REGARDING GOVERNMENT SUPPORT

This invention was made with government support under Contract No. N65540-080D-0017 DP 0001 awarded by the United States Navy. The Government has certain rights in this invention.

## TECHNICAL FIELD

The present invention relates generally to motor drives including active rectifiers, and more specifically to a motor drive including an input electromagnetic interference (EMI) filter.

## BACKGROUND

Electric engine start systems utilize a motor drive (a switching-mode power conversion system) to control a motor/starter and employ an active rectifier as a front-end power converter to interface with a power supply. The active rectifier draws near sinusoidal currents from the power supply to meet specification requirements on input current harmonics. Both the active rectifier and the motor drive inverter employ fast switching IGBT devices controlled using a pulse-width modulation (PWM) technique. The high frequency voltage components of PWM converter (the active rectifier) and inverter cause high frequency leakage currents and conducted EMI in the power lines and ground system.

The conducted EMI can be classified into two-types: common-mode (CM) and differential-mode (DM) according to their circulation paths. The noise flowing within the power-feeding paths is called DM noise, and the noise flowing between the power conversion system and the ground is called CM noise. Typical EMI filters consist of an input section connected between the active rectifier and the power source, and an output section connected between the drive inverter and the motor. Both sections include DM and CM inductors, capacitors and resistors. The output section reduces high-frequency leakage currents due to parasitic motor winding capacitances to ground, as well as bearing currents, and shaft voltage. The radiated emissions are controlled by shielding drive inverter power lines to the motor.

In some systems the motor drive inverter operates at higher output current in comparison to the active rectifier input current that results in a larger weight of EMI filter output section. As an alternative to the excessive weight of EMI filter output section, some systems that operate a motor drive (i.e. engine start) at low duty cycle and utilize shielded output cable to the motor have implemented additional common mode filtering in the EMI filter input section to address additional CM noise contributed by the motor windings capacitive coupling to the ground.

For safety reasons common mode filters do not use an increased total capacitance to ground for filtering. Instead, common mode filters use an increased inductance of at least

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one common mode choke in a multi-stage common mode filter in order to increase the insertion loss of the common mode filter. This construction makes the common mode filter bulky.

## SUMMARY OF THE INVENTION

Disclosed is a poly-phase motor drive including: an input EMI filter having a poly-phase filter input and a poly-phase filter output, an active rectifier connected to the filter output, the active rectifier having a DC output, and a motor drive inverter connected to the DC output, the motor drive inverter having a poly-phase motor control output.

Also disclosed is a method for filtering a poly-phase motor drive including: filtering common mode noise from the switching-mode power conversion system, and filtering differential mode noise from the switching-mode power conversion system.

These and other features of the present invention can be best understood from the following specification and drawings, the following of which is a brief description.

## BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 schematically illustrates a motor drive system including an active rectifier.

FIG. 2 schematically illustrates an example input EMI filter for a motor drive system.

FIG. 3 schematically illustrates an alternate example input EMI filter for a motor drive system.

## DETAILED DESCRIPTION OF AN EMBODIMENT

In existing motor drives, the motor current of the motor drive (the output of the motor drive) is typically higher than the input line current (the input to the active rectifier). An EMI filter at the output of the motor drive must be sized to accommodate the increased motor current resulting in a large physical size of the common mode filter. The higher current requirement of the motor drive inverter requires a lower switching frequency in order to reduce inverter switching losses and improve the thermal performance of the inverter. The lower switching frequency and higher current characteristics of the motor drive inverter lead to an increased size requirement for an output EMI filter.

FIG. 1 schematically illustrates a motor drive 10 including an active rectifier 40 and a motor drive inverter 50 that addresses the above increased size and weight requirements by incrementally increasing an input EMI filter 30 at the active rectifier 40 input and eliminating EMI filtering at the motor drive inverter 50 output. A three phase power source 20 provides electrical power to the motor drive 10. The current from the three phase power source 20 is passed through the input EMI filter 30 to the active rectifier 40. The active rectifier 40 comprises a conventional six-switch voltage source PWM converter and a three-phase boost inductor. In one example, the active rectifier 40 converts a three-phase AC input power into 750 volts DC output power at DC link 42. The switching-mode active rectifier 40 generates high frequency (HF) voltage components that cause HF leakage currents and conducted electromagnetic interference (EMI) noise which flows within power-feeding paths, and between the power conversion system and the ground.

The DC link 42 is connected to an input of the motor drive inverter 50. The motor drive inverter 50, in turn, converts the received DC input power into a three phase AC output power

on lines **52** to power the motor **70**. The motor drive inverter **50** includes a conventional six-switch voltage source PWM inverter. The switching-mode inverter generates high frequency (HF) voltage components that cause HF leakage currents and conducted electromagnetic interference (EMI) noise which flows within power-feeding paths, and between the power conversion system and the ground. Due to the low-duty cycle utilization of the motor drive system for engine start applications, concerns related to the bearing currents and shaft voltage are reduced, while the common-mode noise associated with the high-frequency leakage currents due to motor windings capacitive coupling to the ground are addressed by incrementally increasing size of the input EMI filter.

In some examples, the switching frequency of the active rectifier **40** and the motor drive inverter **50** are the same and introduce the same frequency of common mode noise into the system. In alternate examples, the switching frequencies are different (i.e. the inverter **50** switching frequency may be lower in comparison to the active rectifier **40** switching frequency in order to reduce inverter switching losses when operating the inverter **50** at higher output current levels), and introduce different frequencies of common mode noise into the system.

In the example of FIG. 1, the DC link **42** includes two DC link mid-point capacitors **44** connecting the terminals of the DC link **42**. A bulk capacitor **46** is arranged in parallel to the two DC link mid-point capacitors **44**. A floating point connection **60** connects the input EMI filter **30** to the DC link mid-point capacitors **44**.

FIG. 2 illustrates a first example input EMI filter **30** that can be used in the motor drive **10** of FIG. 1. The input EMI filter **30** includes three phase inputs **103** that connect the three phase power source **20** (illustrated in FIG. 1) to a high frequency CM choke **110**. The high frequency CM choke **110** utilizes a feed-through ferrite toroid and filters out high frequency common mode noise originating from the switching-mode motor drive system **10**.

The output of the high frequency CM choke **110** is connected to a differential mode noise filter **120** and a first notch filter **160**. The differential mode noise filter **120** uses a differential mode inductor on each phase to filter out differential mode noise originating from the switching-mode motor drive system **10**. The first notch filter **160** includes an inductor in series with a capacitor on each phase. The notch filter arrangement filters out noise at the particular switching frequency to which the notch filter **160** is tuned. The output of the first notch filter **160** is connected to the floating point connection **60** via an impedance block **108**.

The output of the differential mode noise filter **120** is connected to a first common mode choke **130** that utilizes a three-phase common mode inductor. Also connected to the output of the differential mode noise filter **120** is a second notch filter **170**. As with the first notch filter **160**, the second notch filter **170** includes an inductor in series with a capacitor on each phase and filters out noise at the particular switching frequency to which the second notch filter **170** is tuned. The second notch filter **170** is connected to the floating point connection **60** via an impedance block **106**.

The output of the first common mode choke **130** is connected to a second common mode choke **140**. As with the first common mode choke **130**, the second common mode choke **140** includes a three-phase common mode inductor. In some example embodiments, the core material of the common mode inductors of the first common mode choke **130** and the core material of the common mode inductors of the second common mode choke **140** are different core materi-

als. In further examples, the core material of the common mode inductors in one of the common mode chokes **130**, **140** is a ferrite material, and the core material in the other of the common mode chokes **130**, **140** is a nano-crystalline materials. The utilization of varied core materials within the common mode inductors of the common mode chokes **130**, **140** allows the input EMI filter **30** to realize benefits of each type of common mode inductor simultaneously.

Also connected to the output of the second common mode choke **140** is a common mode capacitor **180**. The common mode capacitor **180** includes a capacitor on each phase and provides additional filtering. The three phases of the common mode capacitor **180** are tied together and connected to the floating point connection **60** via an impedance block **104**.

Connected to the output of the second common mode choke **140** is a boost inductor **150**. The boost inductor **150** is part of the active rectifier **40** and includes at least one inductor on each phase of the active rectifier **40**. Also connected between the boost inductor **150** and the second CM choke **140** is a differential mode (DM) capacitor/resistor **190** that includes a series connected capacitor and a damping resistor per phase. The boost inductor **150**, DM capacitor **190**, DM inductor **120**, and the first notch filter **160** are a differential mode filter that reduces active rectifier differential mode noise and improves input current harmonic distortions. The first notch filter **160** is tuned to reject current components associated with active rectifier **40** switching frequency. The differential mode capacitor/resistor **190** is connected to the floating point connection **60** via an impedance block **102**.

The arrangement of the differential mode inductor **120**, the boost inductor **150**, and the differential mode capacitor **190** is referred to as a T-type differential mode filter. Each of the differential mode inductor **120**, the boost inductor **150**, and the differential mode capacitor **190** operate in conjunction to provide differential mode filtering of the input to the active rectifier **40**. Similarly, the common mode elements **110**, **130**, **140**, and **180** operate in conjunction with each other to filter common mode noise.

With continued reference to FIGS. 1 and 2, and with like numerals indicating like elements, FIG. 3 illustrates an alternate arrangement for the input EMI filter **30** of FIG. 1. The alternate arrangement varies from the arrangement of FIG. 2 in that the first and second common mode chokes **130**, **140** and the common mode capacitor filter **180** are connected to a single impedance block **202** and the single impedance block **202** connects to the floating point connection **60**. The differential mode capacitor/resistor **190** is connected to the floating point connection **60** via an impedance block **204**, and the floating point connection **60** is connected to a neutral **208** via an impedance block **206**. In both the illustrated examples of FIG. 2 and FIG. 3, the floating point connection **60** is connected to the DC link **42** mid-point as illustrated in FIG. 1.

In a typical example, the impedance blocks **102**, **104**, **106**, **108**, **202**, **204**, **206** are resistive/capacitive (RC) elements. The specific resistances and capacitances of the impedance blocks **102**, **104**, **106**, **108**, **202**, **204**, **206** depend on the needs of the specific system to divert common mode current into DC bus, and can be determined by one of skill in the art having the benefit of this disclosure.

As described above, the active rectifier **40** and the motor drive inverter **50** each operate at a given switching frequency emitting EMI noise associated with these switching frequencies. By way of example, in one motor drive **10** the active rectifier **40** operates at 11 kHz and the motor drive inverter **50** operates at 8 kHz. Thus, additional EMI noise

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will be injected into the system at both 8 kHz and 11 kHz. Each of the notch filters **160**, **170** are tuned to one of the switching frequencies to filter out the EMI noise in that particular frequency.

In alternate systems where the active rectifier **40** and the motor drive inverter **50** are switched at the same frequency, both notch filters **160**, **170** can be tuned to the same frequency, or one of the notch filters **160**, **170** can be omitted entirely. While the notch filters **160**, **170** are described herein as a “first notch filter **160**” and a “second notch filter **170**” it is understood that in a practical implementation the notch filters **160**, **170** are interchangeable and either notch filter **160**, **170** can be tuned to either switching frequency.

While the above motor drive **10** is described and illustrated with regards to a three phase motor drive input filter arrangement, one of skill in the art having the benefit of this disclosure will recognize that the motor drive input filter can be adapted to any poly-phase motor drive and still fall within the above disclosure.

It is further understood that any of the above described concepts can be used alone or in combination with any or all of the other above described concepts. Although an embodiment of this invention has been disclosed, a worker of ordinary skill in this art would recognize that certain modifications would come within the scope of this invention. For that reason, the following claims should be studied to determine the true scope and content of this invention.

The invention claimed is:

1. A poly-phase motor drive comprising:
  - an input filter having a poly-phase filter input and a poly-phase filter output, wherein the input filter includes a high-frequency common mode inductor connected to the poly-phase filter input, a plurality of common mode filter components connected to the high-frequency common mode inductor, and a differential mode damped inductive capacitance filter interconnected with the common mode filter components;
  - an active rectifier including a boost inductor, the active rectifier is connected to the filter output and has a DC output;
  - a motor drive inverter connected to the DC output, the motor drive inverter having a poly-phase motor control output;
  - wherein the differential mode filter is a T-type LC filter; wherein the common mode filter components include a high frequency common mode inductor and are connected to a first shunt-type notch filter; and
  - wherein the common mode filter further comprises a first common mode choke inductor and a second common mode choke inductor, wherein said first common mode choke inductor has a first core material and said second common mode choke inductor has a second core material.
2. The poly-phase motor drive of claim 1, wherein said first shunt type notch filter is tuned to a switching frequency of the active rectifier.
3. The poly-phase motor drive of claim 2, further comprising a second shunt-type notch filter, and wherein the second shunt type notch filter is tuned to a switching frequency of the motor drive inverter.
4. The poly-phase motor drive of claim 3, wherein the switching frequency of the first shunt-type notch filter and the switching frequency of the second shunt-type notch filter are different frequencies.
5. The poly-phase motor drive of claim 1, wherein the first core material is a nanocrystalline material, and the second core material is a ferrite material.

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6. A poly-phase motor drive comprising:
  - an input filter having a poly-phase filter input and a poly-phase filter output;
  - an active rectifier including a boost inductor, the active rectifier is connected to the filter output and has a DC output;
  - a motor drive inverter connected to the DC output, the motor drive inverter having a poly-phase motor control output; and
  - wherein the input filter comprises:
    - a high frequency common-mode choke connected to said poly-phase filter input and having a poly-phase high frequency common-mode choke output;
    - a differential mode inductor block connected to said poly-phase high frequency common-mode choke output and having a poly-phase differential mode inductor block output;
    - a first notch filter connected to the poly-phase high frequency common-mode choke output;
    - a second notch filter connected to the poly-phase differential mode inductor block output;
    - a first common mode choke connected to the poly-phase differential mode inductor block output and having a poly-phase first common mode choke output;
    - a common mode capacitor connected to the poly-phase first common mode choke output;
    - a second common mode choke connected to the poly-phase first common mode choke output and having a poly-phase second common mode choke output; and
    - a differential mode capacitor/resistor block connected to said poly-phase second common mode choke output having an output of said poly-phase filter output.
7. The poly-phase motor drive of claim 6, wherein said first notch filter is connected to a common floating point connection via a first impedance block; said second notch filter is connected to the common floating point connection via a second impedance block; said common mode capacitor is connected to the common floating point connection via a third impedance block; said differential mode capacitor block is connected to the common floating point connection via a fourth impedance block, and said common floating point is connected to DC bus mid-point capacitors.
8. The poly-phase motor drive of claim 6, wherein each of said first notch filter, said second notch filter, and said common mode capacitor are connected to a floating point connection via a first impedance block; said differential mode capacitor block is connected to said common floating point connection via a second impedance block; said floating point connection is connected to a neutral via a third impedance block, and said second impedance block is connected to DC bus mid-point capacitors.
9. A method for filtering a poly-phase motor drive comprising:
  - filtering common mode noise at an input of an active rectifier by passing a received input signal through a first common mode choke constructed with a first core material and passing said received input signal through a second common mode choke constructed with a second core material different from said first core material; and
  - filtering differential mode noise at an input of the active rectifier.



**10.** The method of claim **9**, wherein the step of filtering differential mode noise at the input of the active rectifier comprises filtering differential mode noise in a first frequency band corresponding to a switching frequency of the active rectifier using a first notch filter.

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**11.** The method of claim **9**, wherein the step of filtering differential mode noise at the input of the active rectifier comprises filtering differential mode noise in a second frequency band corresponding to a switching frequency of a motor drive inverter using a second notch filter.

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